THEORETICAL ASPECTS OF HIGH ENERGY NEUTRINOS AND GRB*

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Abstract: Neutrinos at energies ranging from sub-TeV to EeV from astrophysical sources can yield interesting physical information about fundamental interactions, about cosmic rays and about the nature of the sources and their environment. Gamma-ray bursts are a leading candidate source, and their expected neutrino emission can address a number of current questions, which may be answered with forthcoming experiments such as IceCube, Auger, ANITA and KM3NeT.

1. Introduction

The origin of the observed ultrahigh-energy (UHE) cosmic-rays (CRs) above the "ankle", roughly at EeV ($= 10^{18}$ eV) energy, of the CR energy spectrum is most probably extra-galactic. Any galactic origin at this energy, due to small magnetic deflections, would result in an anisotropic distribution of their arrival direction contrary to the observed data. The requirement that they are not attenuated by the cosmic microwave background through photo-meson ($p\gamma$) interactions constrains them to have originated within a radius of 50-100 Mpc, the so-called "GZK" volume.[1,2] Two broad classes of models suggested are the "top-down" scenarios, which attribute UHE-CRs to the decay of fossil Grand Unification defects, and the "bottom-up" scenarios, which assume UHECRs are accelerated in astrophysical sources.

The observed UHECR energy injection rate into the universe is $\sim 3\times10^{44}$ erg Mpc^{-3} yr^{-1} above the ankle. This is similar to the $\sim$ 0.1-1 MeV γ-ray energy injection rate by the local gamma-ray bursts (GRBs) which led to postulating that GRBs are the sources of UHECRs.[3,4] This coincidence has been corroborated using new data and further considerations,[5,6,7]

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making GRBs promising candidates for UHECRs. Other candidates, in the bottom-up scenario, are active galactic nuclei (AGNs), and cluster accretion shocks. An unavoidable by-product of UHECR acceleration is the production of UHE neutrinos, via $p\gamma$ and pp, pn interactions. We limit our discussion to UHE neutrinos from GRBs here.

2. Nature of the High Energy Emission from GRBs

In the most widely accepted GRB model, the *fireball shock model*, the prompt γ-rays are produced by shocks in the plasma material ejected in a jet moving relativistically (with a bulk Lorentz factor $\Gamma \gtrsim 100$), usually taken to be (*internal shocks*), or in other versions an *external shock* (see, e.g., Ref. [8]). Such jets can arise from the core collapse of massive stars, convincingly shown to be the progenitor of long GRBs, or from mergers of compact binary systems (neutron star-neutron star, black hole-neutron star), which may be implicated in producing short GRBs. Late time collision of the jet material with an external medium (external shocks) produce a long lasting x-ray, UV and optical radiation, collectively known as the GRB afterglow.

The highly relativistic nature of the outflows is inferred from and constrained by the observations of GeV photons which avoid attenuation by $\gamma\gamma \to e^{\pm}$ production *in situ*. The probable mechanism(s) responsible for the observed photons is/are synchrotron radiation or/and inverse Compton (IC) scattering by high energy electrons. These electrons are accelerated by the relativistic shocks via the Fermi mechanism in the tangled magnetic field, resulting in a power-law energy distribution. The high bulk Lorentz factors result in synchrotron spectra which in the observer frame extend beyond 100 MeV, and IC scattering of such synchrotron photons leads to the expectation of GeV and TeV spectral components.[9] While $\lesssim 18$ GeV photons have been observed,[10] TeV photons are likely to be degraded to lower energies by $\gamma\gamma$ pair production, either in the source itself,[11] or (unless the GRB is at very low redshifts) in the intervening intergalactic medium.[12,13]

GRBs are likely to be more luminous in neutrinos, gravitational waves and cosmic rays compared to sub-GeV electromagnetic channels which comprise a small fraction of the burst kinetic energy. A significant amount of baryons (neutrons and protons) are expected to be present in the GRB jet along with leptons, each with $\Gamma m_p c^2 \gtrsim 100$ GeV bulk kinetic energy in the observer frame. Protons are also expected to co-accelerate with electrons in the internal and external shocks by the same Fermi mechanism. Using

the shock parameters inferred from broad-band photon spectral fits, one infers that protons can be accelerated to Lorentz factors up to $\lesssim 10^{11}$ in the observer frame, i.e. to the GZK energy of $E_p \sim 10^{20}$ eV.

3. High Energy Neutrinos

High energy neutrinos, detectable by the neutrino telescopes such as IceCube in the $\sim$ 100 GeV-EeV range, are produced in the GRBs in a way similar to the beam-dump experiments in particle accelerators. Shock-accelerated protons interacting with ambient radiation and/or plasma material by photonuclear ($p\gamma$) and/or inelastic nuclear (pp/pn) collisions produce charged pions ($\pi^{\pm}$) and neutral pions (π^0). Neutrinos are produced from $\pi^{\pm}$ decays along with muons and electrons.

Such neutrinos may serve as diagnostics of the presence of relativistic shocks, and as probes of the acceleration mechanism and the magnetic field strength. The flux and spectrum of EeV neutrinos depends on the density of the surrounding gas, while the TeV-PeV neutrinos depend on the fireball Lorentz factor. Hence, the detection of very high energy neutrinos would provide crucial constraints on the fireball parameters and GRB environment. Lower energy ($\lesssim$TeV) neutrinos originating from sub-stellar shocks, on the other hand, may provide useful information on the GRB progenitor.

3.1. *Neutrinos contemporaneous with the gamma-rays*

With an initial $\Gamma_i = 300\ \Gamma_{300}$ and a variability time scale $\delta t = 10^{-3}\delta t_{-3}$ s, internal shocks in the GRB jet take place at a radius $r_i \sim 2\Gamma_i^2 c\delta t \sim 5 \times 10^{12}\delta t_{-3}\Gamma_{300}^2$ cm. The fireball becomes optically thin at a radius $\lesssim r_i$ allowing observed γ-ray emission. Shock accelerated protons interact dominantly with observed synchrotron photons with $\sim$MeV peak energy in the fireball to produce a Δ^+ resonance as $p\gamma \to \Delta^+$. The threshold condition to produce a Δ^+ is $E_p E_\gamma = 0.2\Gamma_i^2$ GeV^2 in the observer frame, which corresponds to a proton energy of $E_p = 1.8 \times 10^7 E_{\gamma,\mathrm{MeV}}^{-1}\Gamma_{300}^2$ GeV. The short-lived Δ^+ decays either to $p\pi^0$ or to $n\pi^+ \to n\mu^+\nu_\mu \to ne^+\nu_e\bar{\nu}_\mu\nu_\mu$ with roughly equal probability. It is the latter process that produces high energy neutrinos in the GRB fireball, contemporaneous with the γ-rays.[14] The secondary π^+ receive $\sim$ 20% of the proton energy in such an $p\gamma$ interaction and each secondary lepton roughly shares 1/4 of the pion energy. Thus each flavor (ν_e, $\bar{\nu}_\mu$ and ν_μ) of neutrino is emitted with $\sim$ 5% of the proton energy, dominantly in the PeV ($= 10^{15}$ eV) range, with equal ratios.

The diffuse muon neutrino flux from GRB internal shocks due to proton

acceleration and subsequent $p\gamma$ interactions is shown as the short dashed line in Fig. 1. The flux is compared to the Waxman-Bahcall limit of cosmic neutrinos from optically thin sources, which is derived from the observed cosmic ray flux.[15] The fluxes of all three neutrino flavors (ν_e, ν_μ and ν_τ) are expected to be equal after oscillation in vacuum over astrophysical distances.

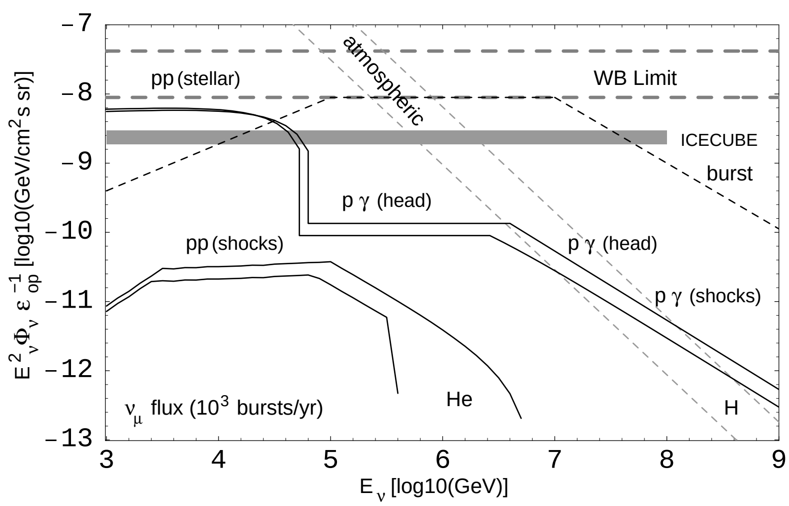

Figure 1. Diffuse ν_μ flux arriving simultaneously with the γ-rays from shocks outside the stellar surface in observed GRB (dark short-dashed curve), compared to the Waxman-Bahcall (WB) diffuse cosmic ray bound (light long-dashed curves) and the atmospheric neutrino flux (light short-dashed curves). Also shown is the diffuse muon neutrino precursor flux (solid lines) from sub-stellar jet shocks in two GRB progenitor models, with stellar radii $r_{12.5}$ (H) and r_{11} (He). These neutrinos arrive 10-100 s before the γ-rays from electromagnetically detected bursts (with similar curves for ν_μ, ν_e and ν_τ).

3.2. *Neutrinos from the GRB afterglow*

The GRB afterglow arises when relativistic jetted plasma material starts being slowed down by the external medium (e.g. the interstellar medium, or ISM), driving a blast wave ahead of the jet. This produces an external forward shock or blast wave, and a reverse shock in the jet. The external shock takes place at a radius $r_e \sim 4\Gamma_e^2 c\Delta t \sim 2 \times 10^{17}\Gamma_{250}^2 \Delta t_{30}$ cm which is well beyond the internal shock radius.[15] Here $\Gamma_e \approx 250\Gamma_{250}$ is the bulk Lorentz factor of the ejecta after the partial energy loss from emitting γ-rays in the internal shocks, and $\Delta t = 30\Delta t_{30}$ s is the duration of the

GRB jet. Neutrinos are produced in the external reverse shock due to $p\gamma$ interactions of shock accelerated protons predominantly with synchrotron soft x-ray photons produced by electrons. The energy of the neutrinos from the afterglow would be in the EeV range as more energetic protons interact with these soft photons to produce Δ^+. The efficiency of proton to pion conversion by $p\gamma$ interactions in the external shocks (afterglow) is typically smaller than in the internal shocks because $r_e \gg r_i$, implying lower photon density.

In the case of a massive star progenitor the GRB jet may be expanding into a stellar wind much denser than the typical ISM density of $n \simeq 1$ cm^{-3}, which is emitted by the progenitor prior to its collapse. For a wind with mass loss rate of $\sim 10^{-5} M_\odot$ yr^{-1} and velocity of $v_w \sim 10^3$ km/s, the wind density at the typical external shock radius would be $\simeq 10^4$ cm^{-3}. The higher density implies a lower Γ_e, and hence a larger fraction of proton energy lost to pion production. Protons of energy $E_p \gtrsim 10^{18}$ eV lose all their energy to pion production in this scenario producing EeV neutrinos.[16]

3.3. *Precursor neutrinos*

In the long duration GRBs, the relativistic jet is expected to be launched near the central black hole resulting from the collapse of the stellar core, hence the jet is initially buried deep inside the star. As the jet burrows through the stellar material, it may or may not break through the stellar envelope.[17] Internal shocks in the jet, while it is burrowing through the stellar interior, can produce high energy neutrinos due to accelerated protons, dominantly below $\sim$ 10 TeV, through pp and $p\gamma$ interactions.[18] The jets which successfully penetrate through the stellar envelope result in GRBs (γ-ray bright bursts), while the jets which choke inside the stars do not produce GRBs (γ-ray dark bursts). However, in both cases high energy neutrinos can be produced in the internal shocks, which slice through the stellar envelope since they interact very weakly with matter.

These neutrinos from the relativistic buried jets are emitted as precursors ($\sim$ 10-100 s prior) to the neutrinos emitted from the GRB fireball in case of an electromagnetically observed burst. In the the case of a choked burst (electromagnetically undetectable) no direct detection of neutrinos from individual sources is possible. However the diffuse neutrino signal is boosted up in both scenarios. The diffuse neutrino flux from two progenitor star models are shown in Fig. 1, one for a blue super-giant (labeled H) of radius $R_* = 3 \times 10^{12}$ cm and the other a Wolf-Rayet type (labeled He) of

radius $R_* = 10^{11}$ cm. The Waxman-Bahcall diffuse cosmic ray bound,[19] the atmospheric flux and the IceCube sensitivity to diffuse flux are also plotted for comparison. The neutrino component which is contemporaneous with the gamma-ray emission (i.e. which arrives after the precursor) is shown as the dark dashed curve, and is plotted assuming that protons lose all their energy to pions in $p\gamma$ interactions in internal shocks.

3.4. *Early np decoupling non-thermal neutrinos*

Neutrons are expected to be present in considerable numbers in the GRB jet ($n_n \simeq n_p$) because of a *neutronized* core similar to that in supernovae in the case of long GRB, and from neutron star material in the case of a short GRB. In the long GRB, the core collapse neutronization leads to copious thermal ($\sim$ 10 MeV) neutrinos, but due to their low energy, their cross section is too small for detection at cosmological distances. However, in both long and short GRB outflows, neutrons are present, and are initially coupled to the protons by elastic nuclear scattering. If the initial acceleration of the fireball is very high, the neutrons can eventually decouple from the fireball, when the comoving expansion time falls below the nuclear scattering time. Protons, on the other hand, continue accelerating and expanding with the fireball as they are coupled to the electrons by Coulomb scattering. The relative velocity between the protons and neutrons, in such a case, can get high enough for inelastic interactions (np) above the pion production threshold of $\sim$ 140 MeV, leading to $\sim$ 10 GeV neutrinos in the observer's frame.[20,21,22] Highly neutron-enriched ($n_n \sim 10 n_p$) jet in case of short GRBs may lead to $\sim$ 50 GeV neutrinos, as the relative velocity between the protons and neutrons increases substantially, which are detectable from a nearby burst.[23]

4. GRB-Supernova Connection

A fraction of long GRBs have recently been shown to be associated with supernovae of type Ib/c.[24] A GRB jet loaded with baryons would then leave long-lasting UHE CR, neutrino and photon signatures in those supernova remnants which were associated with a GRB at the time of their explosion. One example may be the SN remnant W49B which is probably a GRB remnant. A signature of a neutron component in the relativistic jet outflow would be a TeV γ-ray signature due to inverse Compton interactions following neutron decay.[25] Another example may be some of the HESS unidentified sources.[26] Neutron decay would also give rise to TeV neutrinos.

The imaging of the surrounding emission could provide new constraints on the jet structure of the GRB.

Cosmic-rays accelerated in the GRB remnant, similar to SN remnants which are observed as TeV γ-ray sources such as RX J1713.7-3946, would also be expected to produce UHE neutrinos.[27] Expected neutrino and γ-ray energy, commonly originating from $p\gamma$ and/or pp/pn interactions, would be higher in case of GRB remnants because of the higher expansion velocity.

5. Neutrino Flavor Astrophysics

High energy neutrinos from astrophysical optically thin sources are expected to be produced dominantly via $p\gamma$ interactions. Subsequent decay of π^+ and neutrino flavor oscillations in vacuum lead to an observed anti-electron to total neutrino flux ratio of $\Phi_{\bar{\nu}_e} : \Phi_\nu \simeq 1 : 15$.[28] At high energy this ratio may be lower even,[29] since the muons suffer significant electromagnetic energy loss prior to decay.[30] In the case of pp/pn interactions, typically attributed to optically thick sources, $\pi^\pm$ are produced in pairs and the corresponding expected flux ratio on Earth is $\Phi_{\bar{\nu}_e} : \Phi_\nu \simeq 1 : 6$. However even in the optically thin sources the nominal $\Phi_{\bar{\nu}_e} : \Phi_\nu$ ratio may be enhanced above $1 : 15$ by $\gamma\gamma \to \mu^\pm$ interactions and subsequent $\mu^\pm$ decays.[31] The targets are usual synchrotron photons and UHE incident photons are provided by the $p\gamma \to p\pi^0 \to p\gamma\gamma$ channel itself. This mechanism yields an enhancement ratio $\Phi_{\bar{\nu}_e} : \Phi_\nu \simeq 1 : 5$ solely from $\mu^\pm$ decays.

Measurement of the $\bar{\nu}_e$ to ν flux ratios may be possible by IceCube at the Glashow resonant interaction $\bar{\nu}_e e \to W^- \to$ anything at $E_\nu \simeq 6.4$ PeV.[32] Any enhancement over the $1 : 15$ ratio, e.g., from a single nearby GRB would then suggest a $\gamma\gamma$ origin. However, the flux of $\gamma\gamma$ neutrinos depend on the source model such as magnetization, radius etc. We have plotted the $\bar{\nu}_e$ to ν flux ratio in Fig. 2, which includes the contribution from $p\gamma$ and $\gamma\gamma$ channels, from a GRB internal shocks with different model parameters. The solid, dashed, dotted-dash and dotted lines correspond to the magnetization parameter $\varepsilon_B = 10^{-1}$, 10^{-2}, 10^{-3} and 10^{-4} respectively. The shocks take place at the photosphere ($r_{\rm ph}$) and at a radius $10r_{\rm ph}$.[31] Note that the ratio is enhanced from the $p\gamma$ value of $1/15$ in the small energy range where $\gamma\gamma$ interactions contribute significantly. This result then may be used to learn about the GRB model parameters.

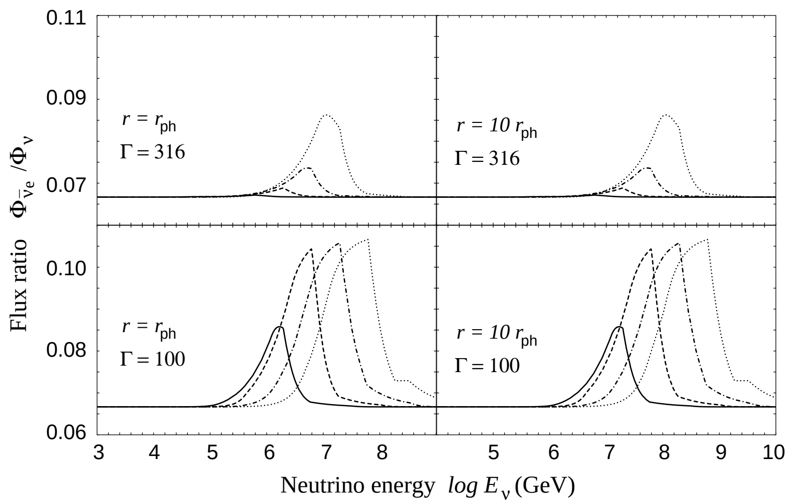

Figure 2. Expected anti-electron to total neutrino flux ratio: $\Phi_{\bar{\nu}_e}/\Phi_\nu$ on Earth from a GRB after vacuum oscillations as function of neutrino energy. The fluxes are both from the $p\gamma \to n\pi^+$ and $\gamma\gamma \to \mu^+\mu^-$ interactions. Depending on the GRB model parameters such as the internal shock radius (at the photosphere $r_{\rm ph}$ and at $10r_{\rm ph}$), bulk Lorentz factor (Γ) and magnetization ($\varepsilon_B = 10^{-1}$, 10^{-2}, 10^{-3} and 10^{-4} denoted by solid, dashed, dotted-dash and dotted lines respectively), the flux ratio may be enhanced from the nominal 1/15 value in certain energy ranges.

6. Conclusions

Although fireball shock model is the leading GRB scenario, there is no strong direct proof so far for the internal shock or the reverse shock origin of the observed radiation. High energy neutrino emission from GRBs would serve as a direct test for this, as well as for "baryonic" jet models, where the bulk of the energy is carried by baryons. On the other hand, an alternative Poynting flux dominated GRB jet model would have to rely on magnetic dissipation and reconnection, accelerating electrons and hence also accelerating protons– but there would be much fewer protons to accelerate and probably to much lower energy.

The *Pierre Auger Observatory*, a CR detector currently under construction, will have very large (~ 3000 km^2 each for its two location in the Southern and Northern hemisphere) area.[33] It will help to disentangle the two scenarios (top-down or bottom-up) and will reveal whether a GZK feature indeed exists by greatly improving the UHECR count statistics. Within the bottom-up scenario, the directional information may either prove or significantly constrain the alternative AGN scenario, and may eventually

shed light on whether GRBs are indeed the sources of UHECRs.

Upcoming experiments such as IceCube,[34] ANITA,[35] KM3NeT,[36] and Auger[33] are currently being built to detect high energy astrophysical neutrinos. They can provide very useful information on the particle acceleration, radiation mechanism and magnetic fields, as well as about the sources and their progenitors. Direct confirmation of a GRB origin of UHECRs is difficult but the highest energy neutrinos may indirectly serve that purpose pointing directly back to their sources. Most GRBs are located at cosmological distances (with redshift $z \sim 1$) and individual detection of them by km scale neutrino telescopes may not be possible. The diffuse neutrino flux is then dominated by a few nearby bursts. The likeliest prospect for UHE ν detection is from these nearby GRBs in correlation with electromagnetic detection.

The prospect for high energy neutrino astrophysics is very exciting, with AMANDA already providing useful limits on the diffuse flux from GRBs[37,38] and with IceCube[39,40] on its way. The detection of TeV and higher energy neutrinos from GRBs would be of great importance for understanding the astrophysics of these sources such as the hadronic vs. the magnetohydrodynamic composition of the jets, as well as the CR acceleration mechanisms involved. High energy neutrinos from GRBs may also serve as probes of the highest redshift generation of star formation in the Universe, since they can travel un-attenuated, compared to the conventional electromagnetic astronomical probes.

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